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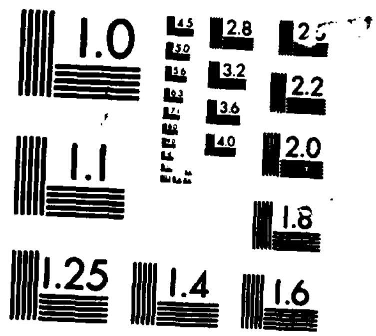

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UNITED STATES NAVAL ACADEMY

DIVISION OF

ENGINEERING AND WEAPONS

ANNAPOLIS, MARYLAND

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Paper presented at 1985 TMS/AIME Annual Meeting 26 February 1985, New York, NY, in Symposium on ADVANCES IN TITANIUM WELDING - Process Advances, Sponsored by the TMS Titanium Committee

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The efficient and cost-effective utilization of conventional and advanced titanium alloys in structural applications has required the advanced development of several welding processes. These developments have been prompted to a great extent by the high reactivity of titanium as compared to other commonly-welded structural metals, but also by titanium's unique physical and metallurgical properties. This review discusses the current state-of-the-art of welding processes for titanium, concentrating on arc and beam welding

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processes. Recent advances in processes designed to weld thicknesses ranging from thin sheet to heavy plate are discussed. The presentation deals with advances in the U.S., however, work conducted abroad is also considered. The general conclusion is that the weldability of titanium and its alloys is excellent. As in the welding of any structural metal, the specific application should be examined to select the best welding process.

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Introduction

The importance and use of titanium and its alloys, as structural materials, have increased since the first U.S. conference in 1948 on their potential (1). Since 1948 significant information on titanium and its alloys has been generated on all aspects of the physical and mechanical properties and fabricability. However, there are still many reservations about its selection which have persisted over the years. For example, machinability and cost are thought to be almost insurmountable and undesirable, while in fact machinability is similar to that in stainless steels and costs based on service life and reduction in maintenance are comparable to other materials in applications where the properties titanium are desired.

As noted by Hanson (2), another common misconception is that titanium cannot be welded. He points out, quite correctly, that all the properties of a material that are of interest in welding are favorable for titanium. For example, its low thermal conductivity reduces the fraction of heat loss in the welding heat input. Low coefficient of thermal expansion minimizes or eliminated the problems of weld cracking and distortion due to contraction on cooling. Also the relatively low density of titanium results in good bead profiles and lack of the weld pool falling through. On the other hand titanium's propensity to absorb and/or react with oxygen, nitrogen, carbon, and hydrogen, especially at temperatures experienced in welding, requires an inert or protective environment for welding.

In order to provide an efficient and cost-effective utilization of conventional and advanced titanium alloys in structural applications, therefore, advances in welding processes have been required. The intent of this review is to discuss current state-of-the-art welding processes which include arc and beam welding processes.

Before proceeding, it is of interest to note the development of welding historically and indicate how the development of welding fortuitously provided welding processes at the time when titanium became viable commercially. In passing, it is of interest to note that the impetus for the development of titanium is due to the development of the gas turbine engine by Sir Frank Whittle (1), visiting Professor at my school from 1977 to 1978. Although electric arc resistance welding was demonstrated by Elihu Thompson in 1886 (3), processes appropriate for titanium were not invented until the mid '30's to early '40's. In 1941 Russell Meredith, Northrop, utilized dcsp heli-arc welding for magnesium aircraft components (4). This is the earliest use of gas tungsten arc welding (GTAW). Submerged arc welding (SAW) was introduced in 1944 (p.149(4)). Gas metal arc welding (GMAW) was developed by Jesse Sohn in 1948 (p.158(4)). Plasma arc welding (PAW) was developed soon after in 1953 by Robert Gage (p.155(4)). Electron beam welding, reported by Steigerwald in 1953 and the Frenchman J.A. Stohr in '54 was the first of the beam welding processes (p.167(4)). Flux core arc welding (FCAW) was developed in the late '50's (5). In this period, Paton of the USSR reported on the electroslag welding (ESW) process (p.43(5)), and in 1960 welding in the vertical position was reported (p.176(4)). Laser beam welding followed in the mid '60's the development of the laser by H. T. Maiman in May 1960 (p. 170(4)).

The impetus for the development of most welding processes was especially devoted to the joining of steels in shipbuilding during and following World War II. The above historical review shows that these developments occurred at a propitious time, when one notes that the commercial age of titanium started about this same time, as shown in figure 1.

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The intent of this review is to discuss current state-of-the-art arc and beam welding processes which are appropriate to structural titanium alloys. Recent advances in processes designed to weld thicknesses from thin sheet to heavy plate will be presented.

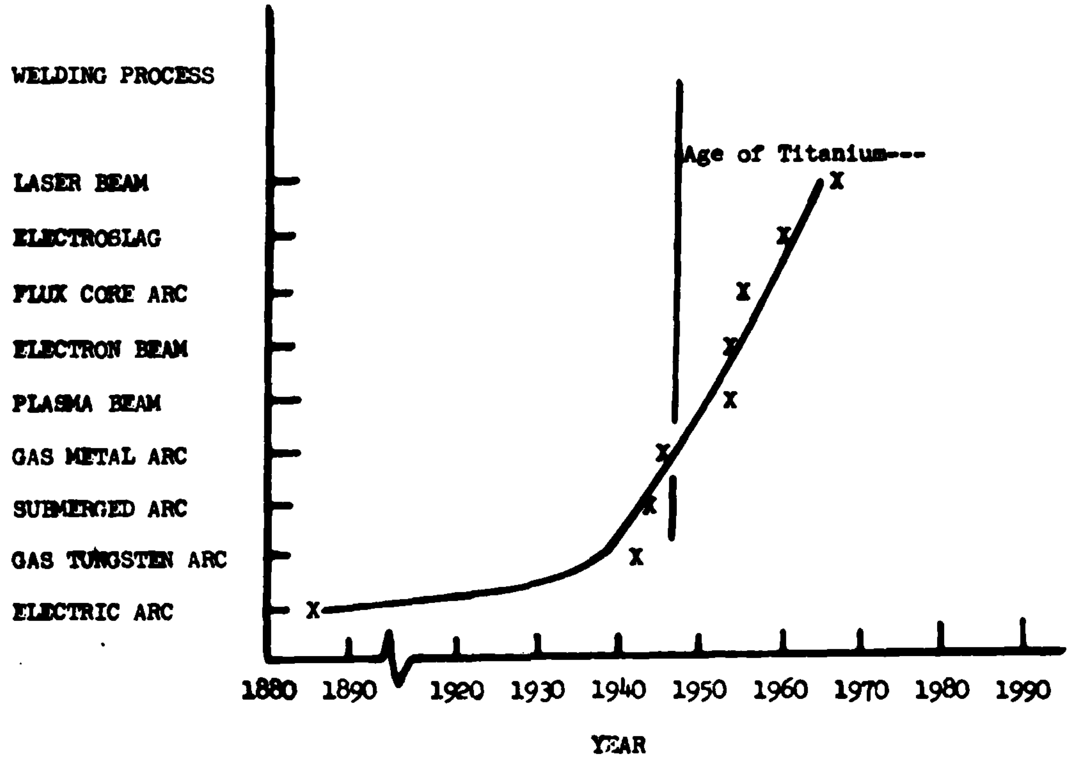


Figure 1.-History of Welding Processes

Welding Processes

The arc welding processes that are utilized for titanium include gas tungsten arc, pulsed arc, gas metal arc, flux core and submerged arc. The electroslag process has also been used. The beam welding processes are electron and laser beam. All these processes are briefly described in the following discussion.

Gas Tungsten Arc Welding (GTAW)

The GTAW process is due to the heating from an arc between a nonconsumable tungsten electrode and the work. Shielding of the electrode and weld zone is accomplished by an inert gas or a mixture of inert gases. The process can be autogenous or filler added automically or manually. One of the early works on titanium for autogenous GTA welding in given in reference (6). A schematic of the torch and work setup is shown in figure 2a. The current type for GTAW is dcsp (electrode negative). The shielding gas is argon for manual and machine welding for material thicknesses under 3.2mm. For material thicknesses over 3.2mm argon-helium is used for manual welding and helium for machine welding (7). Helium is used for thick materials because its high thermal conductivity yields higher available

heat. Inert gas trailing shields are always utilized to prevent contamination of the cooling solidified weld bead. The characteristics of dcsp GTAW welding are a deep narrow penetration with 70% of the heat at the workpiece with excellent electrode capacity.

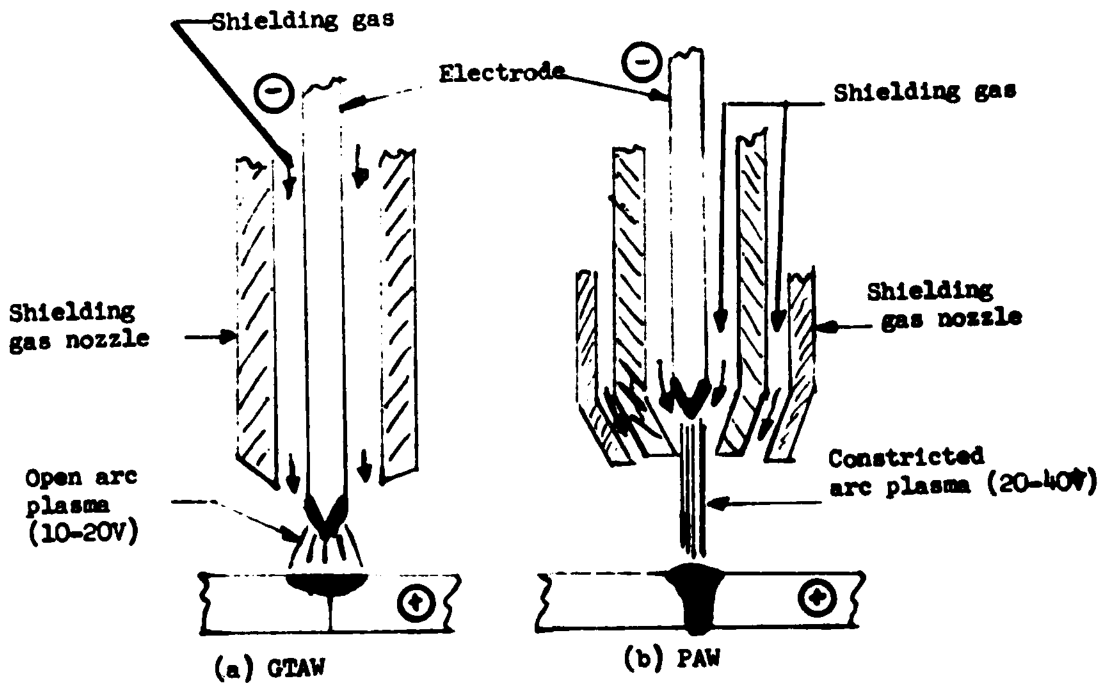


Figure 2.- Schematic of arc welding processes. Note :- GMAW similar to GTAW except the consumable electrode is positive.

Plasma Arc Welding (PAW)

Plasma arc welding is essentially an extension of the GTAW process. The difference is that the arc is passed through a water cooled copper orifice which produces a constricted high energy density arc. For a given welding current, the energy density effective at the workpiece surface is considerably higher for PAW as compared to the GTAW arc. The system also includes shielding gases (eg. argon and/or helium) around the constricted arc. For titanium the polarity is dcsp. Manual or machine welding can be performed either autogenous or with a automatic feed filler system. The system is shown schematically in figure 2b along with the GTAW system to illustrate differences in arc geometry and penetration.

The collimated shape of the plasma jet results in a lack of process sensitivity to arc length changes. A longer permissible torch-to-work standoff distance allows the welder better visibility. Also since the electrode is recessed in the nozzle, it is not possible to touch the electrode to the workpiece which reduces the possibility of tungsten inclusions in the weld. The inert orifice gas also minimized electrode erosion.

One of the chief advantages of the PAW process is the keyhole effect which produces complete penetration and weld uniformity. The greater penetration of PAW compared to GTAW, yields higher depth-to-width ratios in the weld similar to electron and laser beam welding. The keyhole technique also allows for lower heat input which prevents large heat treat effects and grain growth in the metal.

The PAW process with present equipment is limited to metal thicknesses of 25mm or less for butt welds, and it thus cannot achieve thicknesses attainable by electron beam welding (EBW). Mechanized PAW is also generally limited to flat and horizontal positions, while manual welding can be performed in all positions. In addition for PAW, as compared to GTAW, more attention to details, such as, orifice and shielding gas flow rate settings is required of the welder. Other details of the process and variables are described in references (8) and (9).

Gas Metal Arc Welding (GMAW)

The GMAW welding process is similar to GTAW process except the electrode is consumable and the polarity is usually dcrp (electrode positive). The process can be manual or machine but never autogeneous. Dcrp is selected to provide a stable arc, smooth metal transfer with relatively low spatter loss and good weld bead characteristics. Also GMAW is a higher deposition process.

The filler can be transferred either by electrode contact with the weldpool which is called short circuiting transfer or globular or spray of discrete drops from the filler across the arc gap under the influence of gravity or electromagnetic forces. A schematic of the process is shown in figure 2(a) except the consumable electrode is positive.

For titanium alloys which require argon or helium gas shields the initial transfer changes from globular to spray metal transfer at the globular to spray transition current. A variation on the spray welding is the pulsed spray welding process which is capable of all position welding. The power source provides two current levels, one, a steady background current level and two, a pulsed peak current level with a maximum current above the transition current level. The pulsed spray are welding characteristic is shown in figure 3. The effective current for this process is below the current for spray welding, and hence the heat input is lower.

Some of the advantages of GMAW are that it has all welded position capability which for example is a limitation of submerged arc welding, high deposition rate, and deep penetration. Its limitations are as follows: (1) it is difficult to weld in-hard-reach places because the welding gun must be close to the joint, (2) welding arc must be protected against drafts which limits it to indoor welding and (3) weld metal cooling rates are high which could affect the microstructure of heat heatable alloys. Other details on the process for titanium are given in reference (10).

Narrow gap welding is a version of GMAW where deep narrow (about 6 to 10mm) grooves are utilized in thick sections. Specially designed welding torch accessories which include water cooled contact tube and nozzles which introduce shielding gases from the plate surface are employed. Axial spray with dcrp is most often used. Travel speeds are high with resultant low heat input and narrow heat-affect zones (HAZ). This technique provides lower residual stresses and distortion while non-removable defects can occur. No results have been reported for titanium alloys to date.

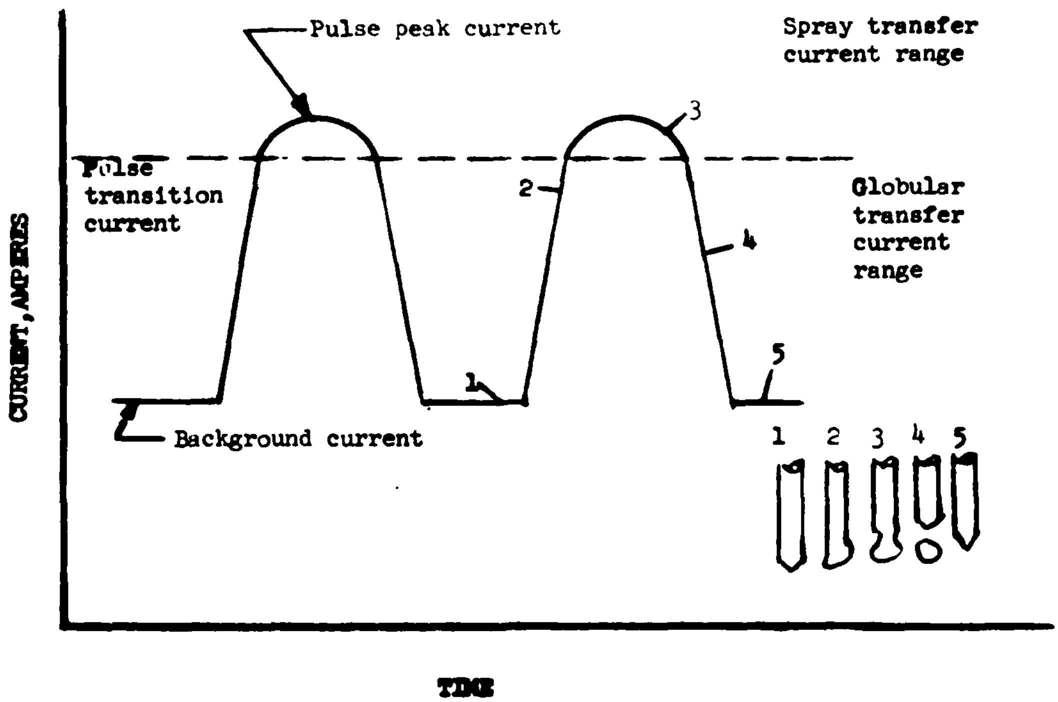


Figure 3.- Pulsed-spray arc welding characteristics.

Flux Cored Arc Welding (FCAW)

The FCAW process is similar to the GMAW process except the consumable filler electrode contains fluxes in its core. A typical setup is shown in figure 4. The process can be manual or machine. Some of the flux in the core provides shielding for the molten weld pool. For titanium, additonal gas shielding of the arc and the weld pool is accomplished by the use of externally supplied inert shielding gases (eg. argon/helium). The electrode core material provides a thin slag covering to protect the solidifying weld metal. Flux cored wire is also used with semi-submerged GTAW welding (11).

When using fluxed wires, deep weld penetration is attained. The deep penetration is caused by arc column contraction at the anode by vapors and the molten flux film. Flux cored wires eliminate the need for storage and handling of the flux. Because of deeper penetration, edge preparation and filler metal consumptions requirements are reduced. Also full penetration welds were achieved in a single pass 3/4 - inch thick titanium plate (12).

Individual components of the flux affect microstructure and consequently the mechanical properties. Sodium fluoride, for example, promotes grain refinement. Gurevich et al (13) have shown significant improvements in impact strengths due to the presence of rare earth fluorides in the flux.

The FCAW process advantages are high deposition rates and lower overall costs per pound of metal deposited. Some disadvantages are the restriction on operating distance from the electrodes and the generation of large volumes of undesirable welding fumes.

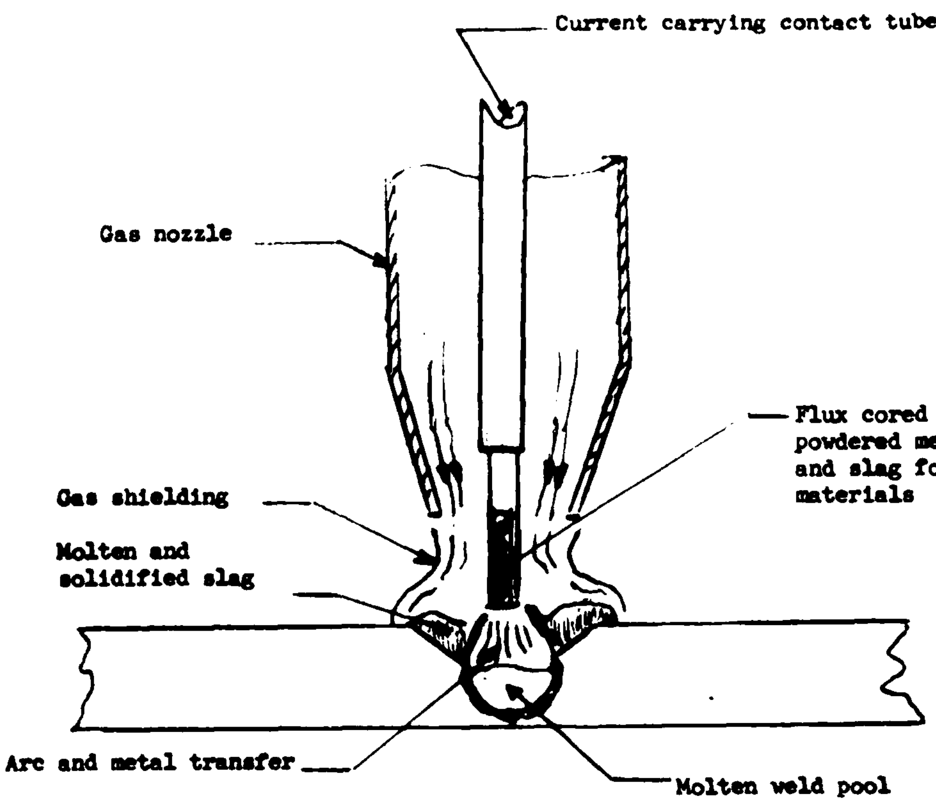


Figure 4.- Schematic of FCAW process with gas shield.

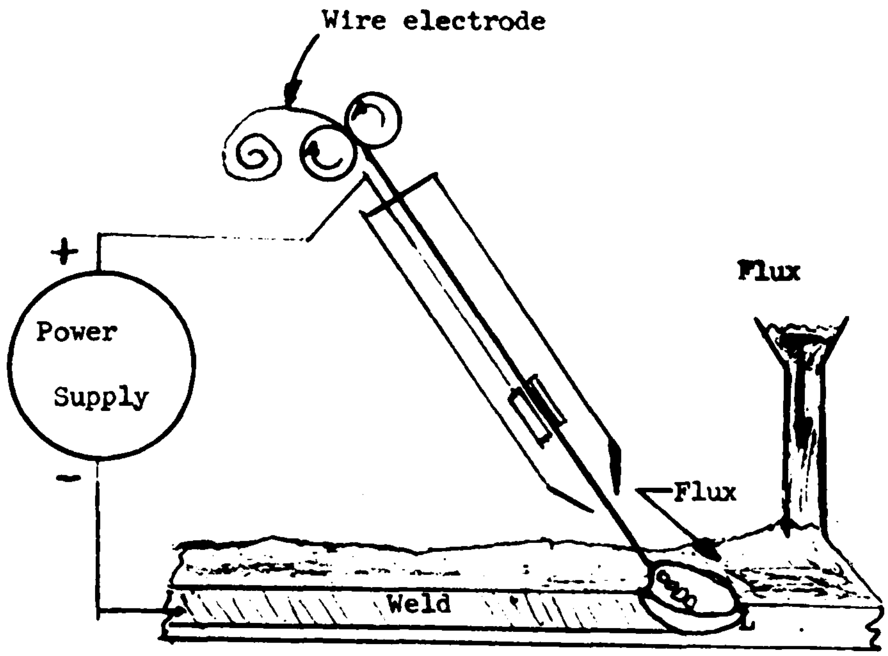
Submerged Arc Welding (SAW)

The SAW process joins the metals to be welded from the heating between a bare electrode and the workpiece. Shielding is provided by a blanket of granular fusible flux over the weld area including coverage of the electrode. A schematic of this system is shown in figure 5 (a). The flux has several functions and plays a major role in achieving high deposition rates and weld quality. Flux composition influences arc stability temperature and heat distribution of the arc plasma. The molten slag promotes slow cooling, and provides the protective atmosphere during cooling. Early work on fluxes was reported by Rosenberg et al (14). Effort on fluxes in the U.S. is described by Eagar and coworkers (15). Early work on the SAW process was reported by Gurevitch et al (16).

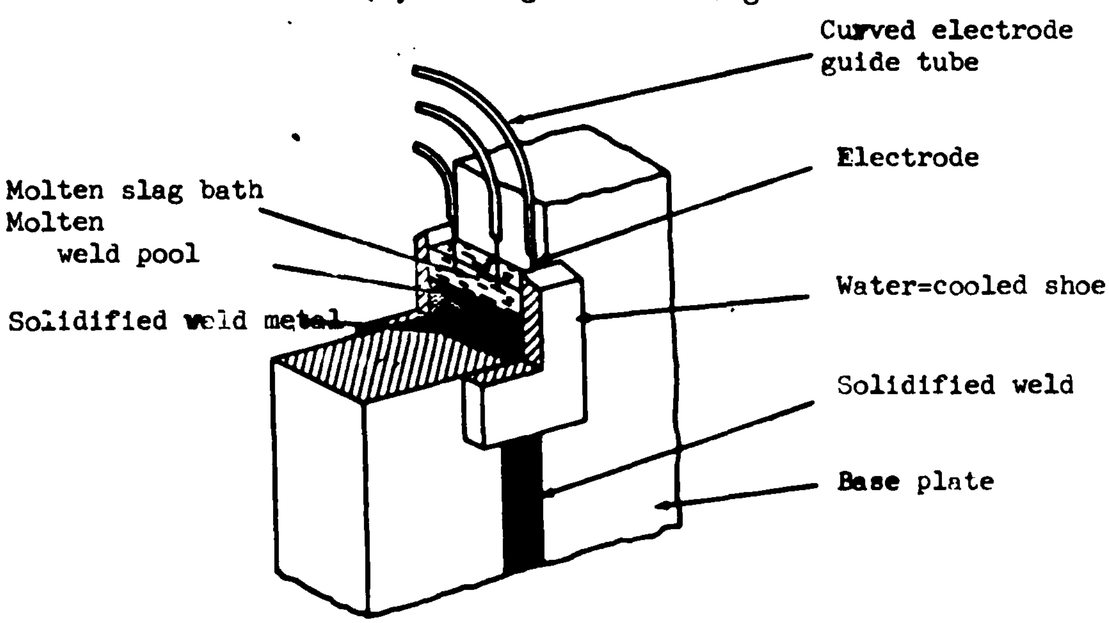
In the process, after arc initiation, the base metal, electrode and flux in the immediate vicinity melt. Electrode and flux material are continually added as the electrode is advanced in the direction of welding.

SAW welding can be performed by the semi-automatic, automatic or machine methods. The weld positions are limited to flat or horizontal fillets. The polarities can be dcrp for small bead shape, dcsp for high deposition rate but with low penetration, and ac which produces penetration depths between the two dc modes.

The weld metal from this process is usually free of undesirable porosity due to protection by the molten slag blanket. The relative slow solidification of this process could cause weld metal cracking, coarse grain structure and component segregation in the weld metal. Changes in welding parameters would be required to avoid these problems.



(a) Submerged Arc Welding



(b) Electroslag Welding

Figure 5.- Schematics of flux weld processes.

Electroslag Welding (ESW)

The ESW process involves melting of the filler and surfaces of the work-piece by a molten slag. The molten weld pool is shielded by the molten slag. The process is initiated by an arc which heats and melts a flux to form the slag. The arc is then extinguished, and the conductive slag in kept in a molten condition by its resistance to the electric current between the electrode and the work. A schematic of the system is shown in figure 5(b). The weld which utilizes copper shoes to contain the weld and slag pool is performed in the vertical position. These are three variations of the process which depend on the thickness to be welded and these are nonconsumable guide with wire electrodes, nonconsumable guide with strip electrode and consumable guide. The setup shown in figure 5(b) is for nonconsumable guide with wire electrodes. The ESW process is especially suited for thick section welding requirements, because it is basically a single pass process. It has definite advantages over the GTAW, GMAW, and SAW processes for thick section welding, because in these multi-pass processes the mechanical properties of the weld and HAZ are affected by continuous heating and reheating during and after each pass which can cause grain growth. This heating and reheating also causes excessive distortion. In addition, it is difficult to keep multipass welds free of porosity and other flaws.

The ESW process and its advantages was discussed in detail first by Gurevitch et al (17) and most recently by Malin (18).

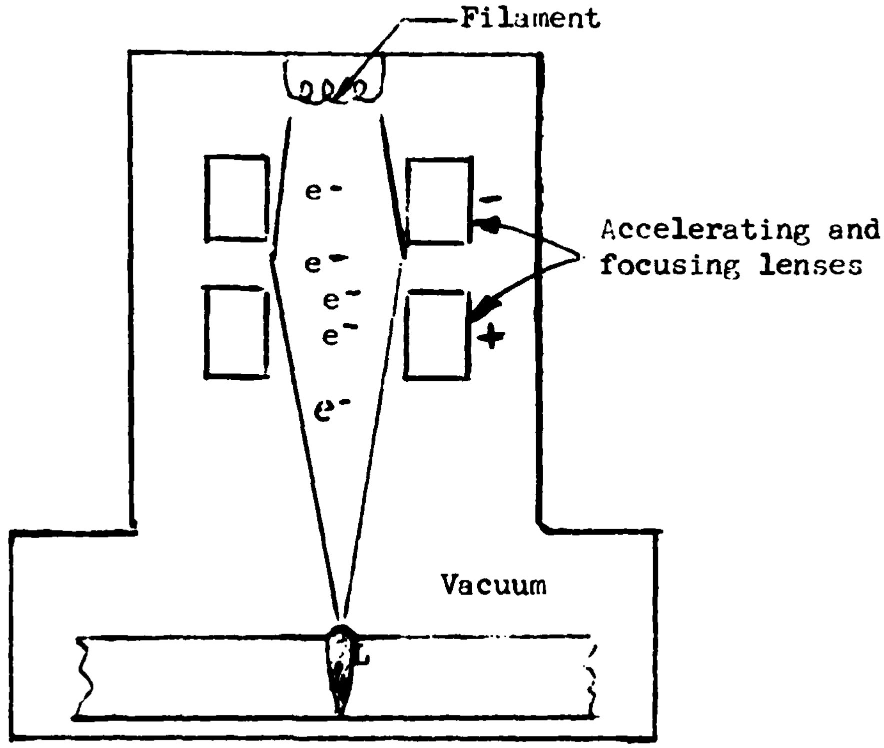
Electron Beam Welding (EBW)

The EBW process is where joining is accomplished by the heat obtained from a concentrated beam of high velocity electrons impinging upon the surfaces to be joined. The electron beam and focusing devices, as well as the workpiece are usually in a high vacuum chamber (10^{-6} to 10^{-3} torr). Chamber size imposes limitations on workpiece size, but the advantage of an inert environment provides the capability for a contamination free weld. A schematic of the system is shown in figure 6a. A successful demonstration of this process for titanium structures was demonstrated by Witt (19).

A variation is the sliding seal (SSEBW) system (20). The system provides a portable vacuum and moving electron beam welding head to avoid the large vacuum chamber associated with electron beam welding. Welding can be accomplished on 0.3 inch plate by this method, but welding of 1.0 inch plate was not successful due to excessive seal wear caused by high heat input, high weld beam crown and poor vacuum capability of the fixture.

An outstanding feature of EBW is the large plate thicknesses to weld width ratios attainable which provides single pass weld capability. The electron beam vaporizes a hole through the entire joint thickness. The walls of the hole are molten, and as the holes moves along, the metal on the advancing side of the hole is melted throughout its depth. The metal flows around the bore of the hole and solidifies along the rear side of the hole to accomplish the weld. Since the heat is localized, the overall heat input to the workpiece is lower than in other welding processes (eg. GMAW). This also reduces distortion in joining, heat affected zone size and grain size in both heat affected and fusion zones.

Since the weld process utilizes butt type joints, costs for beveling or chamfering are eliminated.



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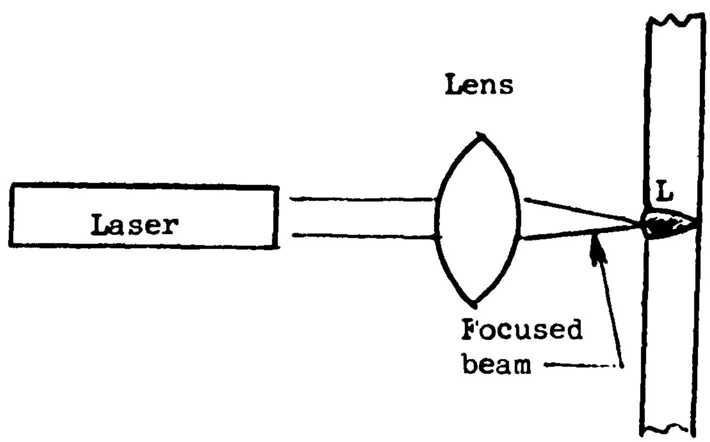

(b)

Figure 6.- Schematic of beam welding processes.

(a) Electron beam and (b) Laser beam.

Laser Beam Welding (LBW)

The LBW process utilizes a laser beam which is a concentrated coherent high beam for heating. The early systems were of the pulsed beam type and the available energy was not sufficient for joining of thick sections. The development of multikilowatt continuous wave (CW) Co_2 lasers around 1970 (21) provided the thick section welding capability.

Energy transfer from the beam causes keyhole formation which is cavity vaporization in the metal. The pressure produced by the vapor in the cavity causes displacement of the molten metal upwards along the walls of the hole. The hole acts as a blackbody and acts as an absorber of the laser beam while distribution heat deep into the metal as opposed to arc processes in which the energy is deposited at the workpiece surface and distributed to the interior by conduction. A schematic of a laser system is shown in figure 6b.

The keyhole cavity contains gas or vapor which are produced by continuous vaporization of the wall material by the beam. The cavity is surrounded by liquid which is surrounded by solid. The flow of the liquid and its surface tension tend to destroy the cavity, while the vapor tends to maintain the cavity. Material flows out of the cavity where the beam enters. For a moving beam, the keyhole achieves a steady state when the cavity and beam associated molten zone move forward at the speed set by the advance of the beam (21). The material lost by vaporization shows up as a bead crown depression as porosity in the solidfied weld metal and/or on inward deformation of the workpiece. Steady state and minimization of the above effects can be controlled by beam advance speed.

The LBW process has the following advantages: (1) due to lack of beam inertia, high processing speeds with rapid starting and stopping are possible; (2) high energy density; (3) welding can be autogeneous; (4) high depth-to-width ratio welds with narrow HAZ can be made; (5) low contamination welds can be made; and (6) complex shapes can be welded by the use of automatic controlled light deflection techniques. Laser beam welding, however, does require inert gas shielding, such as, in GTA and GMA. Typically, a region in front of the beam workpiece interaction site is flooded with helium in order to prevent aspiration of air into the keyhole. A trailing shield is used to protect the molten and hot fusion zones. Also a channel under the joint is flooded with helium to prevent contamination.

Weldability

Weldability is defined as the capacity of the metal to be joined satisfactorily. The criteria are metallurgical compatibility for a specific process (i.e., how the weld region properties differ from the surrounding base metal), ability to produce mechanical soundness (i.e., lack of porosity, inclusions or undesirable phases) and serviceability by under special requirements (e.g. fatigue and/or high temperature). This definition is still applicable, but the study of fundamental metallurgical factors has not received proper attention. Baeslack et al (22) propose a welding metallurgy approach which they define as the merger of the related disciplines of physical and mechanical metallurgy. The merger would provide the understanding of the thermal conditions associated with the welding process and provide a more fundamental understanding of the non-equilibrium thermal conditions which occur in welding. The key to their approach is the utilization of continuous cooling transformation curves. These curves, unfortunately, have not been determined for all titanium alloys of

interest, and this is a definite requirement for future titanium welding research.

The importance of titanium welding metallurgy is due to the fact that the fusion and part of the heat affected zones are heated above and cooled back through the beta transus. The cooling thermal history controls the beta phase transformation characteristics, and consequently the properties of the transformation product and thus the weldability. The transformation product microstructure also determines the extent to which the weld properties can be improved by post weld heat treatment (PWHT). Alpha and near alpha alloys are not significantly affected by the cooling, and usually only a stress relief is required. In contrast alpha + beta alloys are more affected, because the high beta stabilizer content causes a supersaturated martensite product to be produced in the weld zone. This phase can have high strength, but corresponding decreased weld ductility and toughness. Thus weldability depends on the difference in weld zone and base metal hardness. Post weld heat treatment is required to reduce this problem, but sometimes with the attendant decrease in strength of the weld assembly.

The other aspect of weldability, namely, the use of mechanical property tests to determine soundness is also in need of improvement for titanium alloys. While tensile tests, bend tests, Charpy V-notch impact tests and S-N fatigue tests yield useful results, more attention to valid K_{Ic} and fatigue crack growth rate studies are required for advanced high strength titanium alloys to determine the effects of weld defect behavior on structural integrity.

It is noted that good tensile properties such as yield strength and ductility sometimes can be misleading. The author has found that the bend test is a more severe test that will illustrate the presence of contamination effects, porosity and inclusions (i.e. the fractured bend specimen surface will very graphically show these defects).

Mechanical Properties of Welds

The mechanical properties of alpha, alpha + beta titanium alloys welded by the various processes are presented by alloy type in the following discussion. The data does not include all available data, but it is representative.

Alpha and Near Alpha Alloys

The mechanical property and fracture toughness data for these alloys are given in table 1. For commercial pure Ti and Ti-6242 there are data for various weld processes. As might be expected for these essentially non-heatable alloys there is almost no effect on properties due to weld process. Gordine (29) investigated the heat-affected-zone characteristics of GMAW-PC welded Ti-6211. His results are from Charpy V-notch tests and hot ductility measurements. He also includes a CCT diagram for the Ti-6211 alloy. Budillon and Peyronnet (30) welded heavy section, 76mm, Ti-6211 by GMAW, PAW and EBW and found mechanical and toughness properties similar to base material. They also show that the GMAW weld took 69 beads, 76mm high by 50mm wide; while the EBW weld is one bead, 76mm high by 15mm wide including HAZ. Their GMA weld shows that if proper care to avoid interbead contamination and porosity pickup is taken, this process is suitable except for labor cost.

TABLE 1. MECHANICAL PROPERTIES AND K_{Ic} FRACTURE TOUGHNESS FOR ALPHA AND NEAR ALPHA TITANIUM ALLOY WELDMENTS

Alloy	Alloy Type	Weld Process	0.2YS (MPa)	UTS (MPa)	Property e (%)	K_{Ic} $MPa(m)^{1/2}$	Ref
Commercial	Alpha	Base	414	517	25	---	23
		GTAW	441	562	24	---	23
		Base	314	425	22	---	24
		SAW	376	445	19	---	24
		Base	356	422	29	---	25
		ESW	359	429	20	---	25
		Base	>416	>494	27	---	21
		LBW	460-503	530-573	27	---	21
Ti-5Al-2.5Sn	Alpha	Base	723	760	12	52.1	26
Cast ELI		GTAW	723*	775	13	61.9	26
Ti-6Al-2Sn	Near	Base	827	896	10	---	--
-4Zr-2Mo	Alpha	GTAW	945	1090	9	---	27
		GTAW	930**	1000	6	---	28
		EBW	918	1035	12	---	27
		LBW	932	1049	10	---	27
Ti-6Al-2Cb	Near	Base	724	827	14	---	29
-1Ta-1Mo	Alpha	GMAW-PC	---	---	--	---	29
		PAW	---	---	--	70-90	30
		LBW	834-883	924-945	10-19	90	31

*Post weld anneal
**Post weld heat treatment

Alpha + Beta Alloys

Since these alloys are heat treatable and subject to growth of the beta grain size in the HAZ when cooling from above the beta transus, the weld process local heat input can alter ductility and toughness. In addition the weld metal can solidify with large epitaxial beta grains. These effects lead to poor ductility in thin sheet which are welded by the GTAW process. In order to reduce the energy input into the weld zone, processes such as EBW and LBW are preferred. In order to avoid the above problems post weld heat treatment is performed to modify the metastable weld zone microstructure and complete the second step in a two step base metal heat treatment.

Mechanical properties and K_{Ic} fracture data for the most widely utilized titanium structural alloy, Ti-6Al-4V, for various weld processes are given in table 2 (21, 32-38). Satisfactory strength ductility and fracture toughness are attained in welds which are produced by the FBW, EBW and LBW processes. Comparison of the GTAW and EBW processes for sheet from (32) and (38), respectively, show the improved ductility from the LBW process. Welding of thick section material has been primarily by EBW. Gurevich et al (36) report porosity in EBW can be reduced by a remelt pass. LBW, due to porosity, is usually limited to less than 25mm.

Fatigue endurance limits at 10^6 cycles for the Ti-6Al-4V alloy from the various welding processes are given in table 3 from Witt's extensive work (39,40). The base plate material for these welds was in the STOA condition. An additional fatigue limit data point for PAW of 4mm sheet is 552 MPa (41). Vaughan (35) also reports low cycle S-N data for EBW 10mm plate both in the as welded and PWHT conditions. The data of table 3 shows that fatigue endurance is inversely related to weld thickness. Single pass welds (EBW and PAW) were superior in fatigue strength to multiple pass welds (GMAW and GTAW).

Wu (42) reports an extensive welding investigation of the Ti-6Al-6V-2 Sn alpha + beta alloy. Four welding processes, namely manual and automatic GTAW, PAW and EBW were used. He utilized a CCT curve to provide insight into the effect of process heat input, cooling rate, and microstructure on final microstructure and mechanical properties. He reports welding processes of high heat input, such as, manual GTAW, have corresponding low cooling rates which result in tougher weldments. For the low heat input EBW process a PWHT did produce a weld with a yield strength of 1010 MPa and a K_{Ic} fracture toughness of 62.6 MPa $(m)^{1/2}$.

Mechanical property and fracture toughness results on GTAW, PAW and EBW processes of medium strength - high toughness CORONA 5(Ti-4.5Al - 5Mo-1.5Cr) alloy have been reported (22, 28, 43 and 44). The results for autogeneous GTAW on 5mm sheet and autogeneous EBW and PAW on 13mm plate are reported in reference (43), while results for EBW welded 25mm plate are reported in (44). S-N fatigue data are comparable to that for Ti-6Al-4V. Fracture toughness, K_Q, values in the range of 75 MPa $(m)^{1/2}$ are reported (43), and the values are comparable to Ti-662, Ti-64ELI and Ti-6246. Baeslack et al (43) also suggest that fusion welded CORONA 5 can be utilized even when post weld heat treatments are restricted to below 725°C which is temperature normally considered practical for large structural members. It is noted that CCT curves for the CORONA V alloy are utilized by Baeslack and co-workers to optimize fusion zone cooling rates and predict weld properties.

TABLE 2

MECHANICAL PROPERTIES AND K_{I_C} FRACTURE TOUGHNESS FOR Ti-6Al-4V

Weld Process	Thickness mm	Condition	0.2YS (MPa)	UTS (MPa)	e (%)	K_{Ic} MPa(m)$^{1/2}$	Ref
GTAW	5	Base	1284	1313	9.8	---	32
		PWHT	1213	1254	6.7	---	32
EBW	50	Base	950	1051	15	99-112	33
		AW*	967	1107	9	85-92	33
FBW**	40	Base	901	1023	17	---	34
		PWHT	909	1010	12	---	34
EBW	40	PWHT	913	1012	14	---	34
EBW	10	Base	927	991	12	45	35
		AW	935	1030	12	67	35
		PWHT	944	1032	12	64	35
EBW	55	Base	872	911	10	121	36
		AW	911	951	8	81	36
		PWHT	853	882	13	110	36
EBW	90	Base	836	902	14	63	37
		AW	872	943	≈12	---	37
		PWHT	892	956	≈12	66	37
LBW	--	AW	800-860	860-923	11-14	---	21
LBW	3	Base	900	971	12	---	38
		AW	965	1000	11	---	38

*AW - as welded
**Flash butt welded

TABLE 3

FATIGUE ENDURANCE LIMITS AT 10^6 CYCLES FOR Ti-6Al-4V WELDED BY VARIOUS PROCESSES (39)

Thickness (mm)	Weld Process	Fatigue Limit (MPa)
--	Base	≈550
2	EBW	586
2	GTAW	517
6	EBW	517
6	PAW	517
6	GMAW	448
6	GTAW	427
38	EBW	448

Beta and Near Beta Alloys

The mechanical properties and fracture toughness results for these alloys are given in table 4. The Ti-8823 alloy showed the best K_{Ic} fracture toughness was attained by EBW compared to PAW, but for both processes the value is comparable to the alpha + beta Ti-64-alloy (45). Since beta alloys require an aging treatment for greater strength, the values in table 4 are post weld heat treated materials. The fatigue endurance strength values were 414 MPa and 379 MPa for the PAW and EBW welds, respectively.

The tensile property results for the cold formable metastable beta Ti-15-3-3-3 alloys are similar for either the GTAW or LBW processes. The post weld heat treatment (PWHT) of the GTAW welded material gave the same

tensile strength and ductility. Peng et al (46) have studied the correlation between dendrite arm spacing and cooling rate for laser melting of this alloy. Crack growth rate data are also available for EBW of 7.6 mm plate with a K_Q value of about 100 MPa $(m)^{1/2}$ (22). PWHT ageing deteriorated the welded properties by decreasing K_Q to 60 MPa $(m)^{1/2}$ and increasing the crack growth rate.

The tensile values for as welded and PHWT GTAW Ti 10-2-3 welds show the effect of the PHWT which is required to strengthen the as welded retained beta microstructure of this near beta alloy. This strengthening is associated with the formation of an extremely fine, slip impeding alpha morphology during ageing (22) and relatively low ductility.

Continuous cooling transformation (CCT) curves of the Ti-4.5Sn-6Zr-11.5Mo (Beta III) alloy have been reported by Vial et al (47). From this study they indicated that the EBW process should produce a HAZ free of the omega phase, while for GTAW which has a lower cooling rate omega might be formed. They also stated that a five minute PWHT at 510°C might break down the undesirable omega.

Comparison of Welding Processes

Selection of the welding process for the best weldability in a specific application depends on several variables, such as, alloy type, material thickness, size of weld assembly and cost. In a review paper, such as this one, it is impossible to cover all the possible applications. In order to provide some comparisons of the various welding processes, tables based on utilization and cost characteristics similar to the Witt et al (48) 1974 presentation are given in tables 5 and 6, respectively.

TABLE 4

MECHANICAL PROPERTIES AND FRACTURE TOUGHNESS FOR BETA ALLOYS

Alloy	Alloy Type	Weld Process	0.2YS (MPa)	UTS (MPa)	e (%)	K_{Ic} MPa$(m)^{1/2}$	Ref
T-8Mo-8V	Beta	Base	1138	1206	--	54	45
-2Fe-3Al		PAW*	1163	--	3.5	42-50	45
		EBW	1138	--	7	60-64	45
Ti-15V-3Al	Metastable	Base	--	--	--	---	--
-3Sn-3Cr	Beta	GTAW*	725	750	20	---	22
		GTAW*	794	854	18	---	22
		GTAW	690	725	14	---	27
		LBW	662	704	15	---	27
Ti-10V-2Fe	Near Beta	Base	--	--	--	---	--
-3Al		GTAW*	572	842	23	---	22
		GTAW*	759	828	13	---	22

*Properties are for PWHT material

All the weld processes in table 5 are practical for welding sheet. The best processes for fabricators that don't have the expensive EB and LB equipment are the GTAW and GMAW. GTAW can only be single pass welded for 3mm thick material, and for thicker material multipass welds have to be performed. Distortion in thin sheet can be reduced by pulsed-arc GTAW welding (49). Groove joints have to be prepared which cost machining, lost of material and the requirement for filler material. These items with the additional problems of contamination and porosity which can be present in multipass welds make PAW welding attractive for thickness up to 25mm. If the equipment is available, EBW and LBW are also competitive. Both these processes also do not require expensive filler metal. EBW and LBW, because of their low heat input, reduce problems of a wide HAZ. EBW is limited only by the size of the vacuum chamber. All alloy types have been welded by the above processes. Undesirable weld microconstituent effects have to altered or minimized by PWHT. Usually the low heat input processes such as, EBW and LBW are preferable.

Welding processes not presented in tables 5 and 6 are FCAW, SAW and ESW. Their characteristics were previously described in the section on welding processes. These processes which utilize fluxes for shielding from contamination were primarily developed in the Soviet Union due to the unavailability of large quantities of high purity argon gas in the early '60's (50). These processes all provide high deposition rate. The flux in the SAW process helps prevent weld metal porosity. Porosity in all titanium welding processes in primarily due to inadequate cleaning of the base and filler metals. The proposed mechanism for the origin of porosity is that hydrogen enters the weld pool which forms pores on solidification (22). Breme (24) reports the addition of mischmetal to the flux reduces porosity in SAW processed CP Ti.

The ESW process is particularly attractive for thick section pressure vessels. Malin's recent paper (18) provides an excellent description of all aspects of the process. Other descriptions can be found in references (17,51). The process is performed in the vertical welding position. The process doesn't fit the usual aerospace applications, but it is attractive for thick section titanium assemblies. The alloy types that have been welded are of the alpha and alpha + beta alloys. The ESW process, therefore, could be competitive with EBW, because EBW weld assemblies could be limited by the size of available vacuum facilities.

TABLE 5

COMPARISON OF WELDING PROCESS BASED ON UTILIZATION CHARACTERISTICS

Characteristic	GTAW	GMAW*	PAW	EBW	LBW
Thickness, mm	1 to 6	6 to 100	3 to 25	Foil to 75	Foil to 25
Groove Joint Required	Often	Yes	No	No	No
Autogeneous	Often	No	Yes	Yes	Yes
All position Welding	---**	---	---	Yes	Yes
Heat Input	High	High	Moderate	Lowest	Low
Distortion	Very High	High	Moderate	Low	Low
HAZ thickness	Large	Large	Moderate	Small	Small
Contamination Shielding Required	Yes	Yes	Yes	No	Yes
Mechanical Properties	Good-Fair	Good	Good	Excellent	Good-Excellent
Joint Quality	Good	Good	Excellent	Excellent	Excellent

*FCAW would have similar characteristics.
**Penetration characteristics depend on attitude.

TABLE 6

COMPARISON OF WELDING PROCESS BASED ON COST CHARACTERISTICS

	Process				
Cost Factor	GTAW	GMAW	PAW	EBW	LBW
Equipment	≈$16K	≈$20K	≈$20K	≈$100K	≈$200K
Welding (less equipment)	High	Moderate	Low	Low	Low
Filler Required	Often	Always	Sometimes	No	No
V Groove Required	Often	Always	No	No	No

Other Developments in Weld Processes

There have some modifications in the previously discussed weld processes to provide improvements in weldability. Bad'Yanov et al (52) for example, report that the addition of gaseous halogen compounds (eg. SF_6, BF_3, CCl_2F_2, etc.) to the argon shielding gas increases the depth of penetration.

The effect of electromagnetic stirring (EMA) on the weld pool solidification in manual and automatic GTAW to provide grain refinement in the weld metal has been studied in the Soviet Union (53-55), and most recently a study by DeNale and Lukens has been published (56). The Russian investigators report improvements in mechanical properties and corrosion resistance of alpha + beta alloys.

For thin materials, control of heat input into the weld zone either by welding parameters or a change in welding process can be utilized to obtain the best weldability. In thicker sections, however, the use of low energy heat inputs to maintain a small fusion zone grain size is more difficult. One approach to obtain grain refinement in multipass GTAW welds in Ti-6Al-4V was the addition of 0.02 to 0.06 $^{a}/_{o}$ yttrium (57), but only in the center of the weld was grain refined achieved.

In thin plate materials the Soviets (58-59) and Baeslack et al (22) report that the addition of "microcooler" titanium particles in the weld pool can promote fusion zone grain size reductions. Baeslack et al added Ti-6Al-4V REP powder into the trailing edge of a GTAW pool of the near alpha Ti-5Al-5Sn-2Zr-4Mo-0.1Si alloy.

Recently, Wells and Lukens (60) have reported that forced convective cooling by gas jet impingement to weld metals desposited by the GTAW process at heat inputs in excess of 100 kJ/in can refine the macrostructure through control of weld pool geometry. In addition, they found that forced convective cooling increases the depth to width ratio of the weld bead and decreases HAZ width.

A closing hyperbole, might be the thought that the FCAW process could be a forerunner to the development of a "SMAW-like" capability for welding titanium without the use of a expensive-complex inert gas system.

Concluding Remarks

There are numerous weld processes available for the welding of all types of titanium alloys. Welding of thin sheet to very thick plate can be accomplished. Weldability is in general very good, but it could be enhanced with detailed analytic and empirical knowledge of heat (eg. arc transfer efficiency) and fluid analyses. A thermal data base should be developed, and this information could improve the accuracy of presently available CCT curves. The use of CCT curves in conjunction with process cooling rates should also be expanded.

Methods to refine beta grain size and shape would be of value to improve weld mechanical and toughness properties.

The other aspect of weldability, namely, the use of mechanical property tests to determine soundness is also in need of improvement. While the standard tensile and impact tests yield useful results, more attention to valid K_{Ic} and fatigue crack growth rate studies are required for advanced high strength titanium alloys to determine the effect of weld defect behavior on structural integrity.

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